

Comparison of Continuous Electrodeionization Technologies

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ABSTRACT

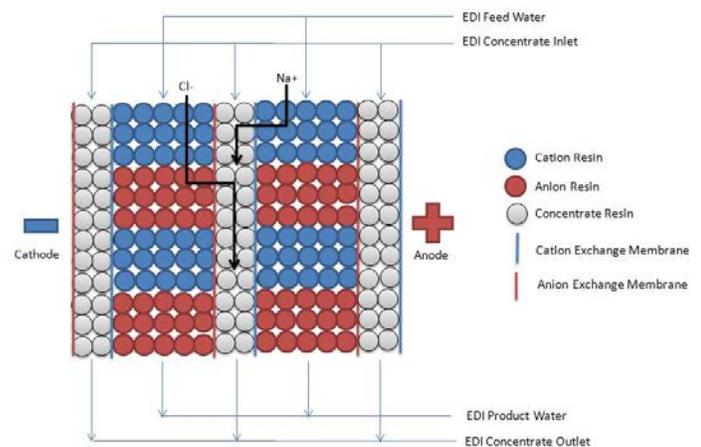
Electrodeionization (EDI) is the standard method of generating high purity water by polishing reverse osmosis permeate. The technology utilizes electrical current to remove ionic impurities while continuously regenerating cation and anion exchange resins. EDI is utilized in all industries that require higher purity water than RO alone can produce including power, pharmaceutical, electronics, laboratories, automotive manufacturing, bottled water and many other industrial applications. There are several commercially available products with identical principles of operation, but differing designs, materials, costs and applications. This paper will review the principles of operation electrodeionization and compare the various commercially available technologies including Ionpure, GE E-Cell, Dow, Qua and Electropure.

Electrodeionization (EDI) is the ultrapure water treatment process which polishes Reverse Osmosis (RO) permeate without chemical regeneration. EDI has been in existence for over 60 years, and has been commercially available for more than 27 years. EDI has become a proven and acceptable technology for all industrial water treatment users that require high purity water. The process of operating an EDI system is extremely simple. Electrodeionization is continuous in nature and sometimes referred to as Continuous Electrodeionization (CEDI) or Continuous Deionization (CDI). There are several different commercially available EDI products with varying design, but all operate using the same principles of chemistry.

Electrodeionization modules are electrochemical devices, driven by electrical energy from an external DC power supply. Each EDI module consists of five primary components: Ion Exchange Resin, Two Ion Exchange Membranes (cation and anion exchange), and Two Electrodes (cathode and anode). Figure 1 shows a schematic diagram of the internal process of one type of Electrodeionization device. Two electrodes are on the ends of multiple cell pairs. Cell pairs include one diluting chamber and one concentrating chamber. As water flows through the EDI module, and power is applied, there are three processes occurring simultaneously: 1) The deionization process where the water is purified by ion exchange, 2) Ion migration where the ions are removed from

the resin, and 3) Continuous regeneration of the resin.

Figure1:

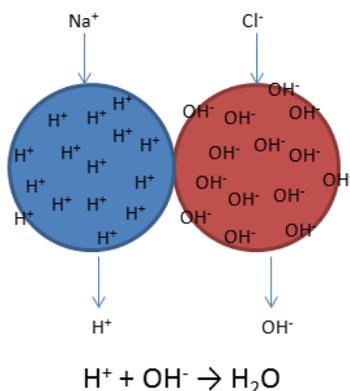


Diluting chambers (D-Chambers) are the portion of a cell pair which contain mixed bed ion exchange resin where water is purified or diluted of ions. Concentrating chambers (C-Chambers) are the areas where water is concentrated of ions, and becomes waste water. The D-chambers contain both cation exchange resin and anion exchange resin. The D and C chambers are separated by ion selective membranes. The membranes are similar in material and charge to the ion exchange resin. Cation exchange membranes only allow cations to pass, and anion exchange membranes only allow anions to pass. Water and oppositely charged ions may not pass across the ion exchange membrane used in EDI.

Deionization is the removal of ions; both positively charged cations and negatively charged anions. Cations are positively charged ions because they have a loss of one or more negatively charged electrons. For example, the sodium ion (Na^+) is positive because the ion lost one electron. Calcium (Ca^{++}) has twice the positive charge of sodium because it has lost two electrons. Anions contain a negative charge because they contain one or more additional electrons. The chloride ion (Cl^-) is formed when chlorine gains one electron.

Figure 2 shows the ion exchange process where resin in the regenerated hydrogen (H^+) or hydroxide (OH^-) form allow the exchange of contaminant cations and anions with hydrogen or hydroxide ions. The released hydrogen and hydroxide ions bond to form water. Water is purified or deionized by the removal of the cations and anions as it flows through the mixed resin bed.

Figure 2



The second simultaneous process in Electrodeionization is ion migration. This

differs from chemically regenerated ion exchange as EDI continuously removes the ions from the resin. Conventional ion exchange resin becomes exhausted until chemical regeneration occurs. Once bonded with the resin, the electrical charge applied at the electrodes attracts the oppositely charged ions. The cations are attracted to the negative cathode and anions are attracted to the positive anode. Positively charged ions will migrate through the cation resin bed, through the cation exchange membrane and into the concentrate chamber due to their attraction to the cathode. Negatively charged ions will migrate through the anion resin bed, through the anion exchange membrane and into the concentrate chamber due to their attraction to the anode. Concentrate and electrode flush water exits the EDI module and is most often sent directly to drain since this is typically only 5-10% of the feed water but could be higher for high scaling or fouling potential. Some EDI devices have a separate electrode flush stream. EDI waste water is typically high quality and can be recovered by the RO inlet by sending it to a ventilated RO feed water storage tank.

The third process that occurs as the ions are removed and migrate to the concentrate chamber is resin regeneration. EDI does not require acid to regenerate the cation exchange resin, nor does it require caustic to regenerate the anion resin. Instead, it takes advantage of the electrical current that is applied across the EDI module. In the presence of the electrical field, a phenomenon known as "water splitting" occurs. The electricity

causes a small percentage of water molecules to split into hydrogen and hydroxide ions which continuously regenerate the resin bed:



Therefore, EDI operation is continuous. The ions are continuously removed, and the resin is continuously regenerated and without chemicals. This provides a significant advantage to ultrapure water users over either onsite or offsite chemically regenerated ion exchange. The operation of the EDI system is as simple as operating a reverse osmosis system and the results of EDI are more reliable.

MANUFACTURES OF EDI

There are many manufacturers of Electrodeionization around the world. The most common devices are Ionpure (USA), GE E-Cell (Canada), Dow EDI (China), Qua (India) and Snowpure Electropure (USA).

Ionpure manufactures plate and frame style EDI devices with “all filled” concentrate chambers and co-current flow path. Flows range from 0.01 gpm to 82.5 gpm per module. Devices are offered in both standard rectangular plate and frame and round disc variations. There are pharmaceutical grade EDI modules available in both chemically sanitizable and instantaneous hot water sanitizable variations. Standard modules have a limit of 1 ppm hardness and high hardness modules have limits of 2 ppm (VNX-HH) and 4 ppm (VNX-CDIT). Standard

modules can tolerate as high as 40 $\mu\text{S}/\text{cm}$ Feed Conductivity Equivalent (FCE) and VNX-CDIT can tolerate as high as 100 $\mu\text{S}/\text{cm}$ FCE.

E-Cell manufactures plate and frame style EDI devices with “all filled” concentrate chambers and a counter-current flow path. Flows range from 2.5 gpm to 28 gpm per module. Devices are offered in standard rectangular plate and frame design. There are pharmaceutical grade EDI modules available which are both chemically and hot water sanitizable. Standard modules have a limit of 1 ppm hardness and high hardness modules are no longer available. Standard modules can tolerate as high as 41 $\mu\text{S}/\text{cm}$ FCE or 25 ppm Total Exchangeable Anions (TEA) or 55 ppm TEA with low flow and warm feed water.

Dow manufactures spiral wound style EDI devices with conductive media concentrate chambers and a cross flow path. Modules have a built in sample port. Flows range from 6.6 gpm to 10 gpm per module. Devices are offered in spiral wound design. There are no pharmaceutical grade EDI modules available. Dow EDI modules have a limit of 0.5 ppm hardness and can tolerate as high as 40 $\mu\text{S}/\text{cm}$ FCE (25 ppm TEA) with a 5 megohm product quality or 8 ppm TEA with 15 megohm. Double pass RO is the preferred pretreatment for Dow EDI, but softened single pass RO can be used in some cases.

Qua manufactures plate and frame style “fractional” EDI devices with unfilled concentrate chambers and a co-current flow path. Flows range from 2.2 gpm to 37 gpm per module. Devices are offered in

standard rectangular plate and frame design with either single voltage or dual voltage options. There are hot water sanitizable variations available. Standard modules have a limit of 0.2 or 1 ppm hardness. High hardness modules with dual voltage and split concentrate flow are available for 2 ppm (FEDI-2) or 3 ppm limits (FEDI-1). Qua EDI modules can tolerate as high as 40 $\mu\text{S}/\text{cm}$ FCE with less than 20 $\mu\text{S}/\text{cm}$ FCE required for ultrapure modules.

Electropure manufactures plate and frame style EDI devices with co-current flow path. Flows range from 0.04 gpm to 39.6 gpm per module. Devices are offered in standard rectangular plate and frame design. There are pharmaceutical grade EDI modules available in both chemically sanitizable and hot water sanitizable variations. Standard modules have a limit of 1 ppm hardness and can tolerate as high as 33 $\mu\text{S}/\text{cm}$ FCE, and < 9 $\mu\text{S}/\text{cm}$ FCE is recommended for optimal performance.

EDI MODULE DESIGNS

Most electrodeionization modules are plate and frame design. The plate and frame normally consists of rectangular dilute and concentrate chambers separated by ion exchange membranes and sandwiched between 2 electrodes. The components are held in place by tie rods or bolts. Due to the uneven pressure distributions as well as the materials of construction and methods of sealing, some plate and frames are prone to leaking. This can be prevented in most cases by following the manufacturer's torquing procedures.

Some modules do not require any torquing, other require torquing bolts once prior to start up and others require torquing as part of a regular maintenance schedule. The benefit of plate and frame designs are that electrical resistance is consistent and current is evenly distributed throughout the device.

Spiral wound EDI modules are manufactured by winding the flat sheet spacers and membranes into a spiral wound element similar to how RO elements are manufactured. Dow Spiral Wound EDI modules connect the center concentrate stainless steel pipe to the DC power source, while the titanium anode lines the inner FRP pressure vessel housing. The benefit to this design is that there are no bolts to torque. The spiral wound EDI is limited by the uneven flow and current distribution.

Ionpure MX and VNX modules utilize a "round disc" plate and frame design. The plate and frame design provides even current distribution. The round plate and frame EDI modules are housed inside a round FRP pressure vessel, eliminating any need for bolt torquing.

DILUTE CHAMBER CONSTRUCTIONS

Prior to 1996, all EDI modules utilized "thin cell" dilute chambers. Dilute chambers contained mixed bed ion exchange resin in 3 mm compartments. The cost of manufacturing such a design was prohibitive for many potential EDI applications, so mixed beds were the standard polishing technology.

In 1997 Glegg's E-Cell introduced the first "thick cell" EDI device which arranged resin in "clusters" of anion and cation resin. This development significantly reduced the cost of manufacturing EDI by reducing the amount of membranes and standardizing the size of modules.

Ionpure introduced the thick cell LX module in 1999. This device utilized a "layered bed" design where resin is arranged in cation and anion resin layers.

Both cluster beds and layered beds have a limited number of cation-anion interaction points and require water splitting for all ion removal. Therefore thick cells operate at low current efficiency. Current efficiency is defined as:

$$\% \text{ Current efficiency} = (\text{Theoretical Current} / \text{Applied Current}) \times 100$$

Where the Theoretical Current is calculated using Faraday's Law based on the concentration of ions removed and the flow per cell.

E-Cell utilizes a similar idea by the reciprocal of current efficiency, called E-Factor.

$$\text{E-Factor} = \text{Applied Current} / \text{Theoretical Current}$$

For example a typical EDI system may be designed for 10-20% current efficiency, or an E-Factor of 5-10.

Snowpure's Electropure dilute chamber is considered thin cell by comparison to thick cell design with a 4 mm thickness.

Qua's FEDI is a device that splits its dilute stream into two passes. The first pass is operated at lower current with less water splitting to reduce hardness. The second pass is operated at a higher current to increase water splitting and remove weakly ionized species.

Recent research and product development resulted in a thin cell innovation called the VNX-CDIT. This design benefits from an all-filled thin cell configuration minimizing problems with concentration polarization. The resulting device is an EDI which can handle much higher concentrations of hardness, silica, CO₂ and ions.

The VNX-EP is a specially configured resin configuration for the power industry that provides low sodium and low silica product water.

Table 1 differentiates current EDI module D-Chamber thicknesses. Thin cell devices operate at lower current efficiencies while thick cells utilize less membrane area. Low current efficiency does not necessarily result in low power consumption unless concentrate chambers have low electrical resistance.

Table 1

| Dilute Chamber | Thickness |
|----------------|--------------|
| Thin Cell | 3.0 – 4.0 mm |
| Thick Cell | 8.0 – 9.1 mm |

CONCENTRATE CHAMBER CONSTRUCTIONS

Early versions of electrodeionization modules include a mesh concentrate spacer. The mesh provides support to the membranes. The mesh is typically a nonconductive polymer which results in high electrical resistance, voltage and power consumption. The early method of reducing the resistance was by recirculating a large portion of concentrate outlet to the inlet, increasing concentrate conductivity. Another method to increase conductivity was by injecting a food grade salt into the concentrate chamber to further reduce electrical resistance. Concentrate recirculation is not desirable as the scaling and fouling contaminants being removed are recirculated in higher concentrations than in the feed water. Brine injection is difficult to maintain consistent conductivity and results in salt in unattractive locations. Mesh has also been shown to be problematic with biofouling. The concentrate chamber is prone to hardness scaling especially in systems operated with low current efficiency, so a design with maximum durability is desired for optimal performance.

Ionpure introduced a patented "All Filled" design in 1996 which includes resin in both the dilute chamber and concentrate chambers. The resin is a conductive media and allows efficient and even current passage with lower voltage and power consumption. While previous generations E-Cell MK-1 & MK-2 required concentrate recirculation and sometimes brine injection, GE introduced an all filled

design with the current MK-3 module in 2007 followed by the larger E-Cell-3X module in 2011.

Dow uses a concentrate screen that has been treated to provide ion exchange properties, thus becoming ionically conductive. This eliminates the previously required concentrate recirculation and brine injection.

Snowpure reports that the Electropure modules use a thin concentrate spacer approximately 0.7 mm thick with woven fiber mesh. Concentrate flows through in a once through path. This design requires that concentrate conductivity be maintained between 10-100 $\mu\text{S}/\text{cm}$. Single pass permeate is sometimes used as EDI concentrate feed with 2 pass RO feed to increase concentrate conductivity. Alternately brine injection can be used in those cases.

Qua EDI uses a once through concentrate flow, but brine injection is required in some cases.

E-Cell is the only device that provides a "counter flow" concentrate design. In this design concentrate enters next to the dilute outlet end exits adjacent to the concentrate inlet. Therefore hardness does not pass all the way through the concentrate stream. In this design higher feed pressure is required to maintain lower dilute pressure than concentrate pressure. Co-current flow is possible with hardness less than 0.1 ppm as CaCO_3 .

SINGLE PASS OR TWO PASS RO PRETREATMENT

The pretreatment design and membrane selection is critical to a successful EDI installation. The EDI modules selected along with the knowledge and experience of the process design engineer will determine whether the RO can be single pass or double pass.

Single pass RO systems have higher concentrations of scaling and fouling contaminants such as hardness, silica and organics. Additionally the performance can be affected by conductivity, scaling or fouling and higher CO₂. Sodium hydroxide injection prior to the RO membranes is a low cost method of controlling CO₂. By raising the pH, the RO membranes become more prone to scaling due to higher Langlier Saturation Index (LSI). Double pass RO with caustic injection prior to second pass or membrane degasification provides the lowest stress to an EDI unit, however has the highest capital cost and is not always needed.

Some EDI suppliers are working to reduce the overall system cost by eliminating the need for a second pass RO. Other EDI suppliers prefer two pass RO. Dow offers an extended warranty for systems with 2 pass RO feed.

There are many successful installations of EDI with single pass RO around the world. One provided by Agape Water Solutions in 2006 has single pass RO feed treating 900-1200 microsiemens/cm and over 300 ppm hardness as CaO₃. In 2014, the EDI

system with a standard module is producing 17 megohm-cm.

PERFORMANCE

All EDI manufacturers market a product water of up to 18 MΩ-cm, but such a product quality will greatly depend on the EDI feed water. Different EDI modules will produce different product qualities even with the same feed water. Little research has been done to compare the performance of different EDI modules or standardize testing for comparative evaluation.

During the preparation of this paper, each EDI manufacturer was requested to provide guaranteed product quality of various feed waters. Feed water sources outlined in Table 2 were selected from actual EDI projects with a variety of combinations, single pass or double pass RO, softened or unsoftened, caustic injection or no caustic injection. Ion concentrations are listed in ppm as ion. Ionpure, GE and Dow provided their product quality if an EDI module is available to treat the feed water. For standard comparison, 50 gpm product flow and 60 °F feed water was utilized.

Table 2

| Case: | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|-----------------|-------|-------|------|------|------|------|------|
| Ca | 0.2 | 0.21 | 0.00 | 0 | 0.5 | 0.03 | 0.06 |
| Mg | 0.06 | 0.06 | 0.00 | 0 | 0.12 | 0.01 | 0.05 |
| Na | 0.56 | 0.43 | 0.18 | 0.82 | 1.01 | 2 | 0.76 |
| K | 0.00 | 0.09 | 0.01 | 0.01 | 0.06 | 0.06 | 0.05 |
| NH4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Ba | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Sr | 0.00 | 0.00 | 0 | 0 | 0.01 | 0.01 | 0 |
| CO3 | 0.00 | 0 | 0 | 0 | 0 | 0 | 0 |
| HCO3 | 2.09 | 1.80 | 0.44 | 0.73 | 3.63 | 3.63 | 0.92 |
| SO4 | 0.02 | 0.02 | 0.01 | 0.02 | 0.07 | 0.07 | 0.04 |
| Cl | 0.15 | 0.14 | 0.04 | 0.36 | 0.89 | 0.89 | 0.95 |
| F | 0.00 | 0.00 | 0.00 | 0 | 0 | 0 | 0 |
| NO3 | 0 | 0 | 0.00 | 0.85 | 0.30 | 0.30 | 0.07 |
| SiO2 | 0.24 | 0.23 | 0.05 | 0.12 | 0.12 | 0.11 | 0.46 |
| CO2 | 0.31 | 8.07 | 0.2 | 13.8 | 16.8 | 16.8 | 1.24 |
| pH | 7.09 | 5.6 | 6.61 | 4.95 | 5.59 | 5.59 | 6.13 |
| TEA | 3.8 | 13.5 | 0.82 | 20.9 | 39.2 | 39.2 | 4.41 |
| FCE | 5.29 | 26.9 | 1.49 | 31. | 56.9 | 56.9 | 9.15 |
| Hardness | 0.731 | 0.771 | 0.01 | 0 | 1.76 | 0.12 | 0.4 |

Table 3 shows the performance of various EDI modules with unsoftened single pass RO feed described in cases 1, 2 and 7. Hardness in these cases are less than 1 ppm as CaCO₃.

Table 4 shows the performance of various EDI modules with typical 2 pass RO feed (case 3) and feed water treated with softened single pass RO feed water (case 4).

Table 5 shows the performance of various EDI modules with high hardness (case 5) and high CO₂ (case 6).

Table 3

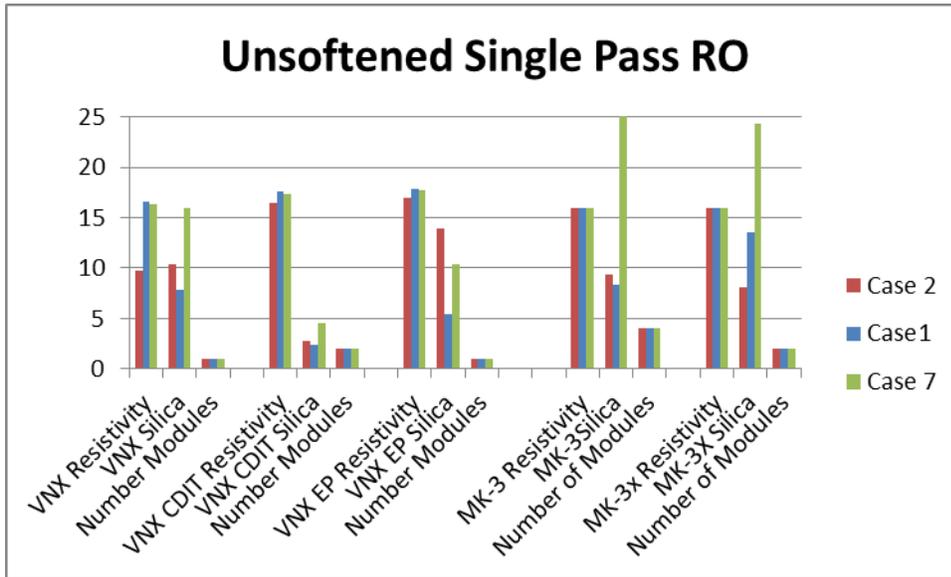


Table 4

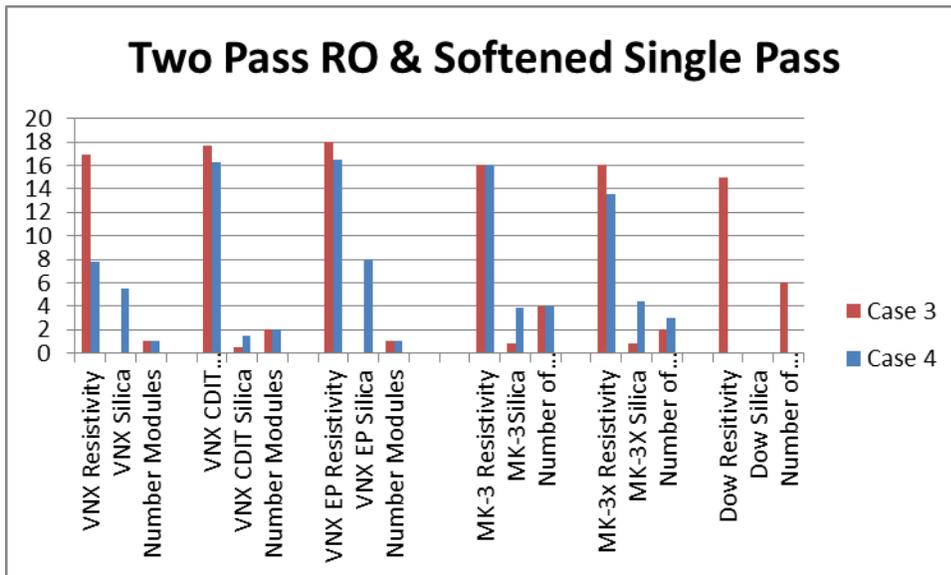
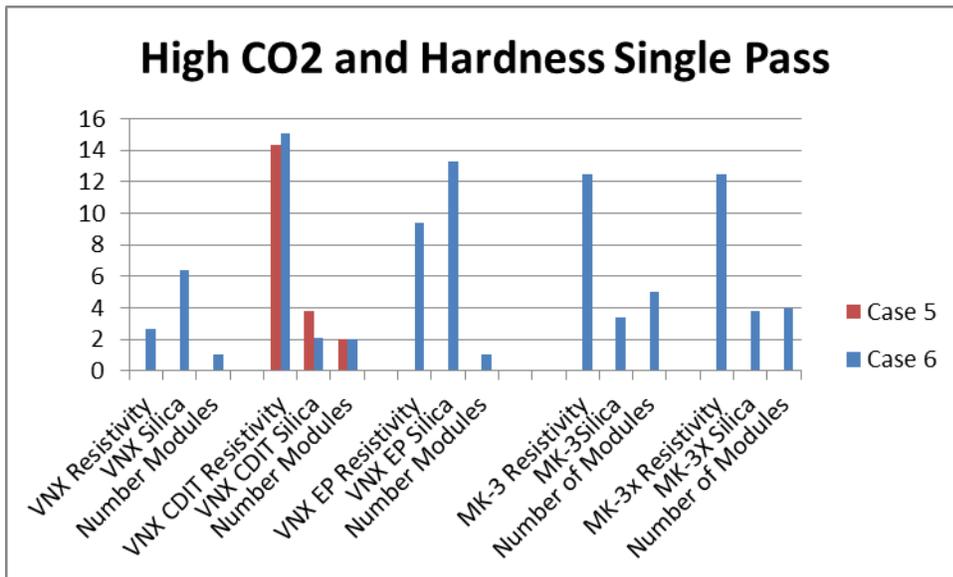


Table 5



CONCLUSIONS

Electrodeionization is a reliable and cost effective technology for the production of ultrapure water. There are many available EDI modules on the market and the

selection of the optimal EDI module depends on the performance required, feed water source, and available budget. Double pass RO is not always required depending on the modules selected.

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